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# PRELIMINARY ANALYSIS OF WAVE ENERGY CONVERSION AT AN OFFSHORE STRUCTURE



SEPTEMBER 1982

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# **PRELIMINARY ANALYSIS OF WAVE ENERGY CONVERSION AT AN OFFSHORE STRUCTURE**

by

A. DOUGLAS CARMICHAEL, D. ASSANIS, J. O. SALSICH

of

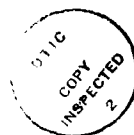
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ABSTRACT

A study of the feasibility of utilizing wave energy to provide the electrical power to operate the Buzzards Bay Light Tower has been carried out. It was concluded that a pneumatic buoy attached to the light tower would be the best solution. Experiments were conducted in the MIT Towing Tank to estimate the performance of such a device. The loads imposed by the wave energy device on the tower during an extreme storm were estimated and were predicted to be very large. Theoretical and experimental studies have indicated a possible method of reducing the size of the wave energy device by controlling the air pressure in the buoy.

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NOMENCLATURE

a	device radius
A	function, equation (3.3)
B	function, equation (3.4)
$C_D$	drag coefficient
$C_m$	inertia coefficient
D	device diameter
g	acceleration due to gravity
$h_o$	inside wave height
H	wave height
$H_o$	incident wave height
$H_{100}$	one hundred year maximum wave height
$H_s$	significant wave height
$I_1$	Bessel function
$J_1$	Bessel function
k	wave number, $\omega^2/g$
$K_1$	Bessel function
$l$	capture width
L	wave length
$\bar{P}$	average power
$\Delta P_o$	peak to trough pressure change
T	wave period
$T_p$	peak wave period
u	function, equation (3.3)
$Y_1$	Bessel function
$\rho$	water density
$\omega$	wave circular frequency

## 1. INTRODUCTION

The utilization of renewable energy resources is being considered as part of the continuing study of the provision of power for the various light stations around the U.S. coastline. Wave energy is one of the renewable resources available at some sites. Several wave energy conversion devices have been developed (mainly in Europe and Japan) which have demonstrated good efficiency, at least in laboratory settings. It was therefore decided to examine the feasibility and viability of supplying much of the power needed at an offshore light station through wave energy conversion using the Buzzards Bay Tower as a case study.

### 1.1 POWER REQUIREMENTS

The information on the power predictions for the various light stations has been described in a recent U.S. Coast Guard report [1]. At the Buzzards Bay Light Tower, the radio beacon operates continuously and is estimated to consume 213 watts, the light signal equipment estimated consumption is 2,470 watts for the lamps and the motor during the hours of darkness, and the sound signal only operates during foggy conditions and has a power consumption of 425 watts, but peaks at 1,632 watts. In addition to these AC power consumers there are several monitoring and radio link devices which consume about 155 watts (DC).

Using the method described in the recent U.S. Coast Guard report [1] it was assumed that the representative day

has 11 hours of daylight, 13 hours of darkness and 2.4 hours of fog. The representative 24 hour usage of electrical power is therefore:

Radio Beacon	213 watts for 24 hours
Lamp Signal Equipment	2470 watts for 13 hours
Sound Signal	425 watts for 2.4 hours
Monitoring, Radio Link	155 watts (DC) for 24 hours

The power requirements for the representative day corresponds to average values of approximately 1.6 kW of AC power and 0.16 kW of DC power. For preliminary design purposes it has been assumed that the net power delivered to the existing systems on the Buzzards Bay Tower should average 2 kW. Since the conversion equipment and energy storage system have losses, it is obvious that the power that should be absorbed from the waves to satisfy this power level must be in excess of this value. A means of storing energy (such as lead acid batteries) would probably be used to absorb high energy generated during storms, for use later during periods of calm seas. The utilization of energy storage when alternate energy systems are used at remote sites has been described in a U.S. Coast Guard report [1].

## 1.2 EXISTING WAVE ENERGY CONVERSION DEVICES

Many wave energy conversion devices have been described in patents and in the technical literature. Much of the recent effort has emphasized systems that are capable of producing

large power outputs (several megawatts). Such devices are difficult to scale down to low power levels (several kilowatts) because one characteristic dimension, often the draft (but it could be diameter or length) is proportional to the wave length, for good performance. However, because many of these new devices operate at resonance, reducing the characteristic size to reduce power makes them operate inefficiently off-resonance. Hence, even though the required power output is small, for the light tower application, the physical size of such devices would be large, and large size imposes considerable loading on the tower in storms.

Problems may also arise because of the inevitable changes in the directions of the waves. The complexity and cost of providing a mechanism to set the converter to the prevailing wave direction, it was felt, would eliminate the possibility of using unidirectional devices. Unfortunately, many of the well known energy conversion devices are unidirectional; these include the Salter Duck, the Hagen - Cockrell Raft, the French Air Bag, the Evans Cylinder, the NEL Water Column Device, and the Kaimei Ship [2]. What remains are multidirectional devices, often termed point absorbers. The original Masuda Air Buoy can be considered to be a point absorber. Other point absorbers are the bullet-shaped buoy device described by Budal and Falnes and the Vickers submerged resonant duct; these devices are described in the published technical literature [2].

During the initial phases of this study it was concluded that unidirectional devices were unlikely to be suitable for application at light towers. Furthermore, it was decided that moving mechanical systems placed in the region of the air-sea interface would not prove to be very reliable because of corrosion, ice, and storm damage. It was therefore determined that pneumatic conversion devices would be investigated, since all the mechanical moving parts could be placed some distance above the ocean surface. Pneumatic devices are those in which air is compressed by wave action and the compressed air drives a turbine or air motor. The original Masuda Air Buoy is a form of pneumatic device and it was thought that as a result of recent theoretical hydrodynamic studies such devices could be improved and optimized.

## 2. WAVE ENERGY ENVIRONMENT

The wave climate at the Buzzards Bay Tower was measured and reported by Thompson of the Army Corps of Engineers [3]. The information was presented as significant wave height,  $H_s$ , and peak period,  $T_p$ , and is displayed as a scatter diagram on Figure 2.1. This diagram indicates the number of occurrences in parts per 1000. Lines of constant power in kW per meter of wave crest are superimposed on the scatter diagram. Lines of constant power were calculated from the equation for waves in deep water.

$$\text{Power} = \frac{\rho g^2}{64\pi} H_s^2 T_p^2 \quad (2.1)$$

where  $\rho$  is the sea water density

$g$  is the acceleration due to gravity.

The information presented in the scatter diagram can be reorganized to provide the average annual power level at each wave period from 1 to 15 seconds as shown on Figure 2.2. The sum of these individual average power levels is the overall average at the wave energy site. Based on the data of Thompson this value is 3.3 kW per meter. Much of the wave power is at wave periods from 5 seconds to 12 seconds.

The information on wave direction at the Buzzards Bay site has not yet been established. Wave direction is

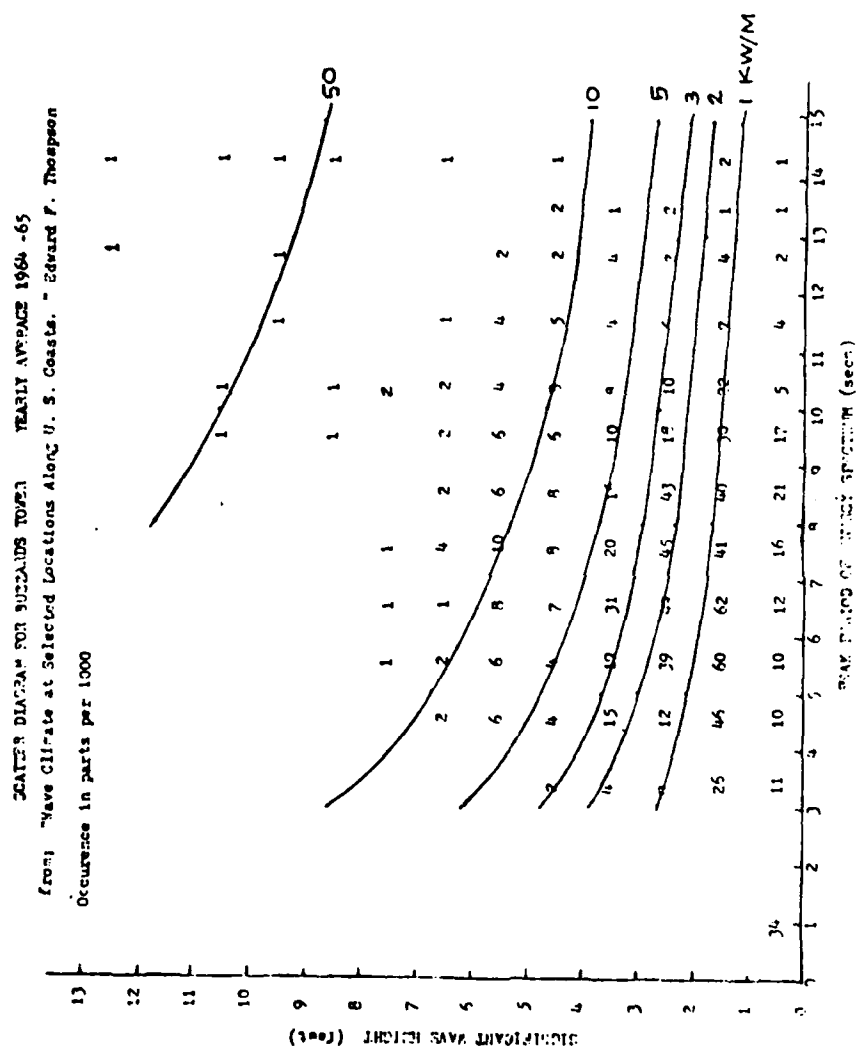


Figure 2.1 Scatter Diagram for the Buzzards Bay Site



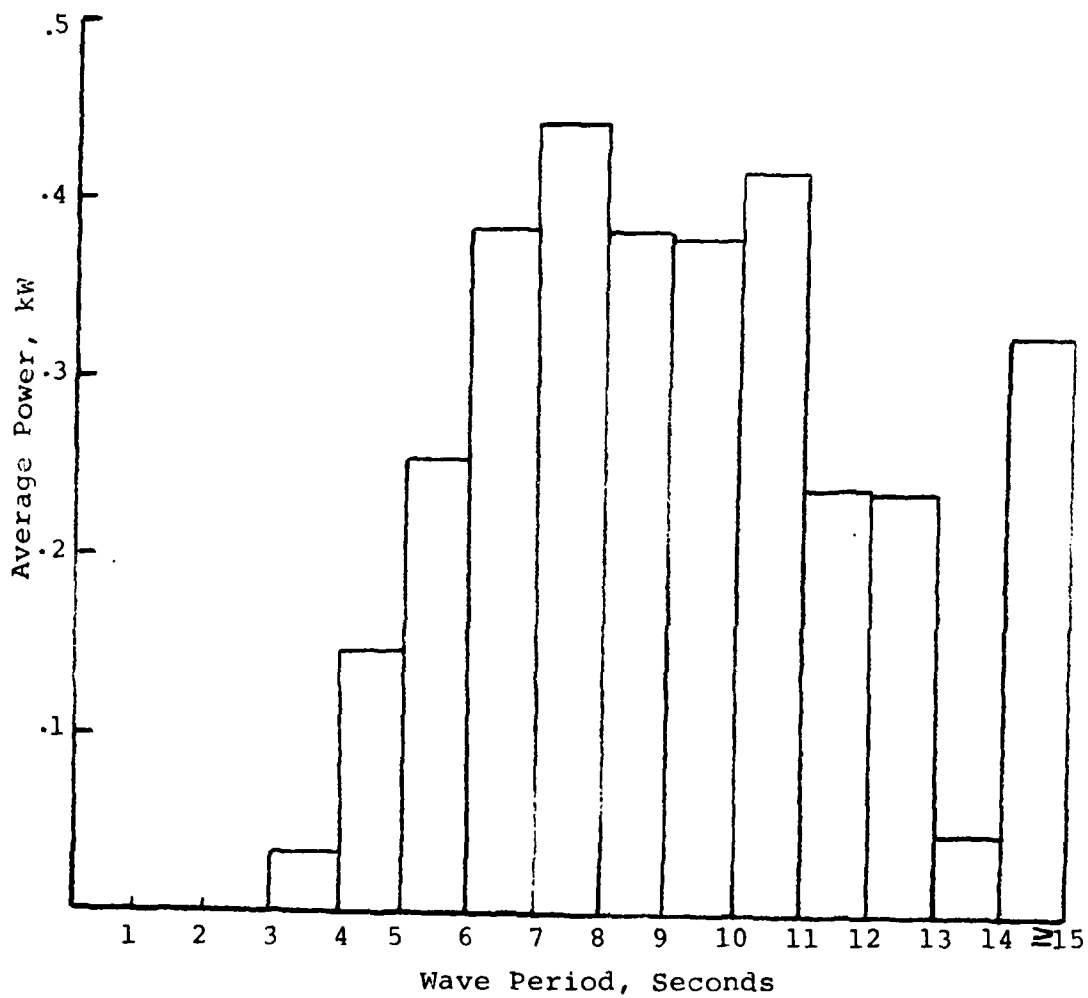


Figure 2.2 Expected Average Wave Power at the Buzzards Bay Tower in Each Wave Period

particularly difficult to measure as a routine matter. However, it is known that the general direction of winds is from the SW in summer and from the NE in winter.

### 3. HYDRODYNAMIC ANALYSIS

Theoretical studies of wave energy devices by Count [2], Newman [4], Evans [5], and others have provided a clear description of the operation of ideal wave energy converters. Although various wave energy devices may have very different geometries and operating principles, nevertheless, it has been demonstrated that their performance characteristics are often very similar.

Evans [6] in a recent paper, described a theoretical analysis applicable to pneumatic wave energy absorbers similar to the devices proposed for the Buzzards Bay Light Tower. This analysis agrees with the general results given by the earlier methods, but it applies directly to pneumatic devices. It is therefore useful for comparison with the experimental results presented in the next chapter.

All the theoretical methods ([2], [4], [5], and [6]) show that the maximum ideal power occurs when the wave energy absorber is in resonance with the incident waves, or, more precisely, when the absorber has the same phase as a resonant device. In this ideal situation the maximum power that can be absorbed by an axisymmetric device in regular deep water waves is given by the equation:

$$\bar{P}_{\max} = \frac{\rho g^2 H^2 T}{32\pi} \left( \frac{L}{2\pi} \right) \quad (3.1)$$

where

$\bar{P}_{\max}$  is the average maximum power  
 $g$  is the acceleration due to gravity  
 $\rho$  is the density of water  
 $H$  is the wave height, trough to crest  
 $T$  is the wave period  
 $L$  is the wave length

The term  $(\rho g^2 H^2 T / 32\pi)$  is the power available per unit of wave crest width, therefore equation (3.1) shows that an ideal device at optimum conditions has a "capture width" equivalent to the wavelength,  $L$ , divided by  $2\pi$ . Capture width,  $\ell$ , defines the width of wave crest that has the same wave power as that absorbed by the wave energy device. The capture width divided by diameter,  $\ell/D$ , is analogous to efficiency, and provides a measure of the power absorbed by a wave energy device compared to the power that is available in a wave having a crest width equivalent to the diameter of the converter.

Evans [6] provided a method for predicting the general performance of an ideal axisymmetric wave energy absorber at resonant and nonresonant conditions. The method assumes a very shallow device composed of an air chamber, radius  $a$ , sitting on the surface of the water. Evans demonstrated that the capture width,  $\ell$ , was given by the expression:

$$\ell = 2[1 + (1 + \omega^2 A^2 / B^2)^{1/2}]^{-1} k^{-1} \quad (3.2)$$

In this expression A and B are functions of ka:

$$A = - (2\pi a^2 / \rho g) \left[ \pi J_1(ka) Y_1(ka) + (2ka/\pi) \int_0^\infty \frac{I_1(u) K_1(u)}{u^2 + k^2 a^2} du \right] \quad (3.3)$$

$$B = (2\pi^2 a^2 \omega / \rho g) J_1^2(ka) \quad (3.4)$$

where  $J_1$ ,  $Y_1$ ,  $I_1$ , and  $K_1$  are Bessel functions in the usual notation

$k$  is the wave number,  $\omega^2/g$

$a$  is the radius of the device

Evans determined from these equations that resonance would occur at  $ka = 1.96$ , where the capture width ratio,  $\ell/D$ , would be only 0.26. As  $ka$  is reduced the value of  $\ell/D$  increases until it peaks at a value of 0.4 when  $ka$  is 0.7. This is a non-resonant condition and the performance improvement comes about because the increased wave length at low wave number has more than compensated for operation away from resonance.

The theoretical analysis of an idealized model of a pneumatic wave energy absorber has indicated that the predicted performance is likely to be rather disappointing. The device is only expected to absorb about 40% of the incident wave power. However, there are several possibilities for improving the performance that will be evaluated experimentally. First, the resonance condition can be moved to a

lower frequency by increasing the mass of water moved in the device (by increasing depth or draft). Secondly, it may be possible to achieve an artificial resonance by active control of the air pressure in the wave energy absorber. These possibilities will be discussed in the next chapter.

The idea of achieving artificial resonance with pneumatic devices does not appear to have been suggested before. Although, Falnes and Budal [7] have described successful operation with artificial resonance used on a floating buoy. To achieve the phase angle of resonant operation in a pneumatic wave energy device it would be necessary to control the air pressure to be in phase with the incident waves.

#### 4. EXPERIMENTAL STUDY OF PNEUMATIC WAVE ENERGY DEVICES

A series of tests on small models of pneumatic wave energy absorbers was conducted in the Towing Tank of the MIT Ocean Engineering Department to evaluate their performance. These tests were described by Salsich [8]. Many of the tests were carried out on a small circular cylindrical device with a small orifice in the top to represent the load imposed by a turbine.

##### 4.1 EXPERIMENTAL ARRANGEMENT

The tests were conducted in a 100 ft. long, 8 ft. wide, and 4 ft. deep towing tank. The paddle wavemaker is hydraulically operated, and has a frequency range of 0.5 to 2.0 Hz. There is a beach with damping material placed at the remote end from the wavemaker to minimize wave reflections.

The main tests were carried out on a 6 inch nominal diameter cylinder having an overall length of 6.5 inches. The bottom of the cylinder was open and the top was closed with a cap; instrumentation was placed in the cap. The main measuring instruments were a resistance wave probe and a pressure transducer. The load of the air turbine was simulated by orifices of various sizes, placed in the cap, which could be selectively opened or sealed. The wave probe and the pressure transducer were calibrated before each series of tests.

The pneumatic wave energy absorber models were placed approximately in the middle of the towing tank and supported rigidly, to represent operation from a light tower. They were tested at wave periods from 0.6 to 1.5 seconds, at various drafts, and over a range of orifice sizes. The published reports on two-dimensional pneumatic devices had indicated that the best performance occurred with an orifice size having a flow area equivalent to about one percent of the water plane area inside the device. The experiments at MIT tended to confirm this observation.

Modifications, made later in the test program included the incorporation of air valves to control the air pressure inside the model. The valves were operated by electromagnets.

#### 4.2 EXPERIMENTAL RESULTS

The power of the wave energy absorber model was determined by calculating the rate of doing work at the interface between the water column and the air in the cylindrical device.

The performance characteristics for the six inch diameter model with a 1% orifice area are presented in Figures 4.1, 4.2, and 4.3. In these figures the results are plotted against non-dimensional frequency,  $\omega\sqrt{D/g}$ . Non-dimensional frequency is related to the parameter  $ka$ , used in the hydrodynamic analysis described in the previous chapter, by the equation:

$$\omega\sqrt{D/g} = \sqrt{2ka} \quad (4.1)$$



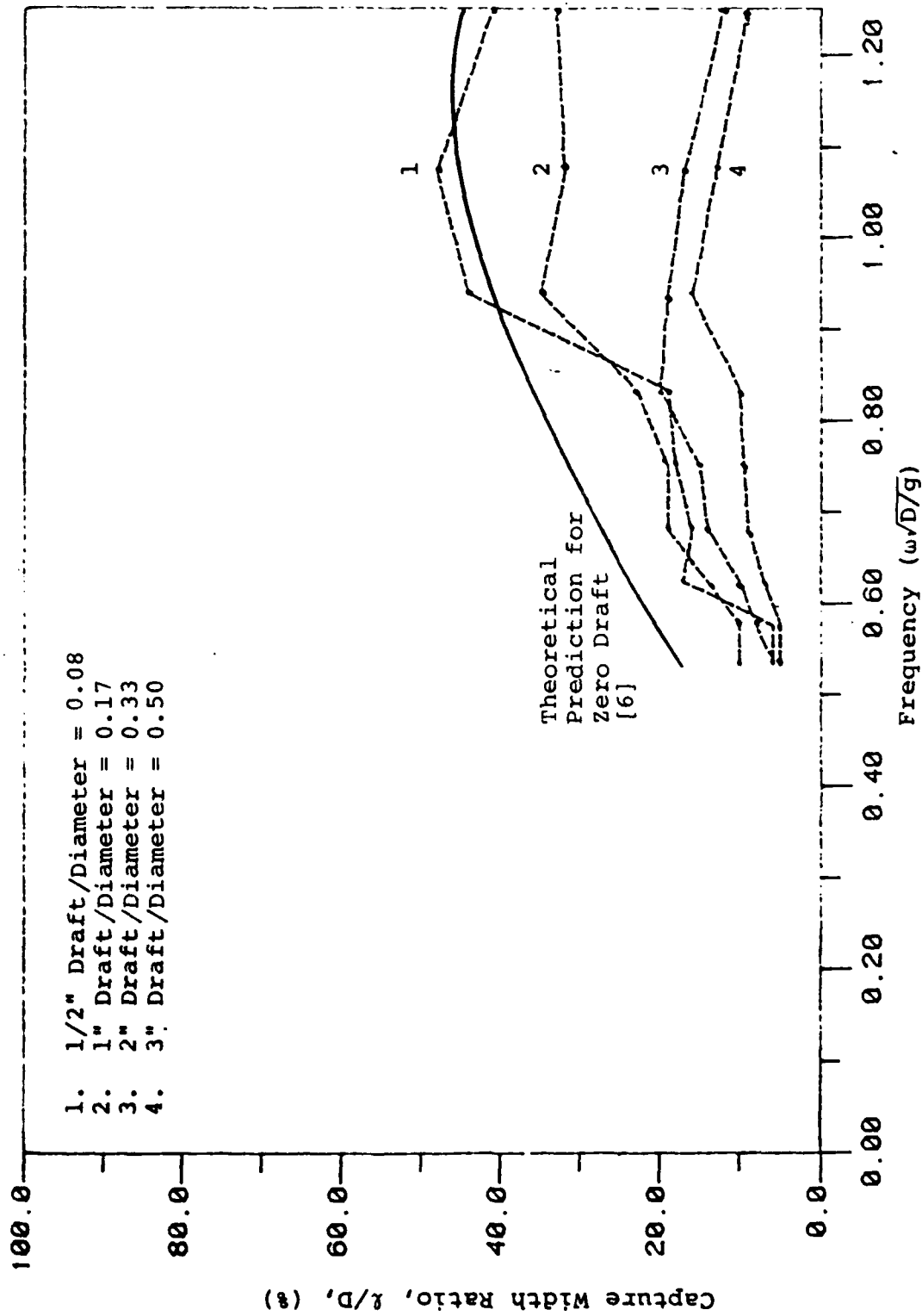


Figure 4.1 Capture Width Ratio of 6" Cylinder, 1% orifice area

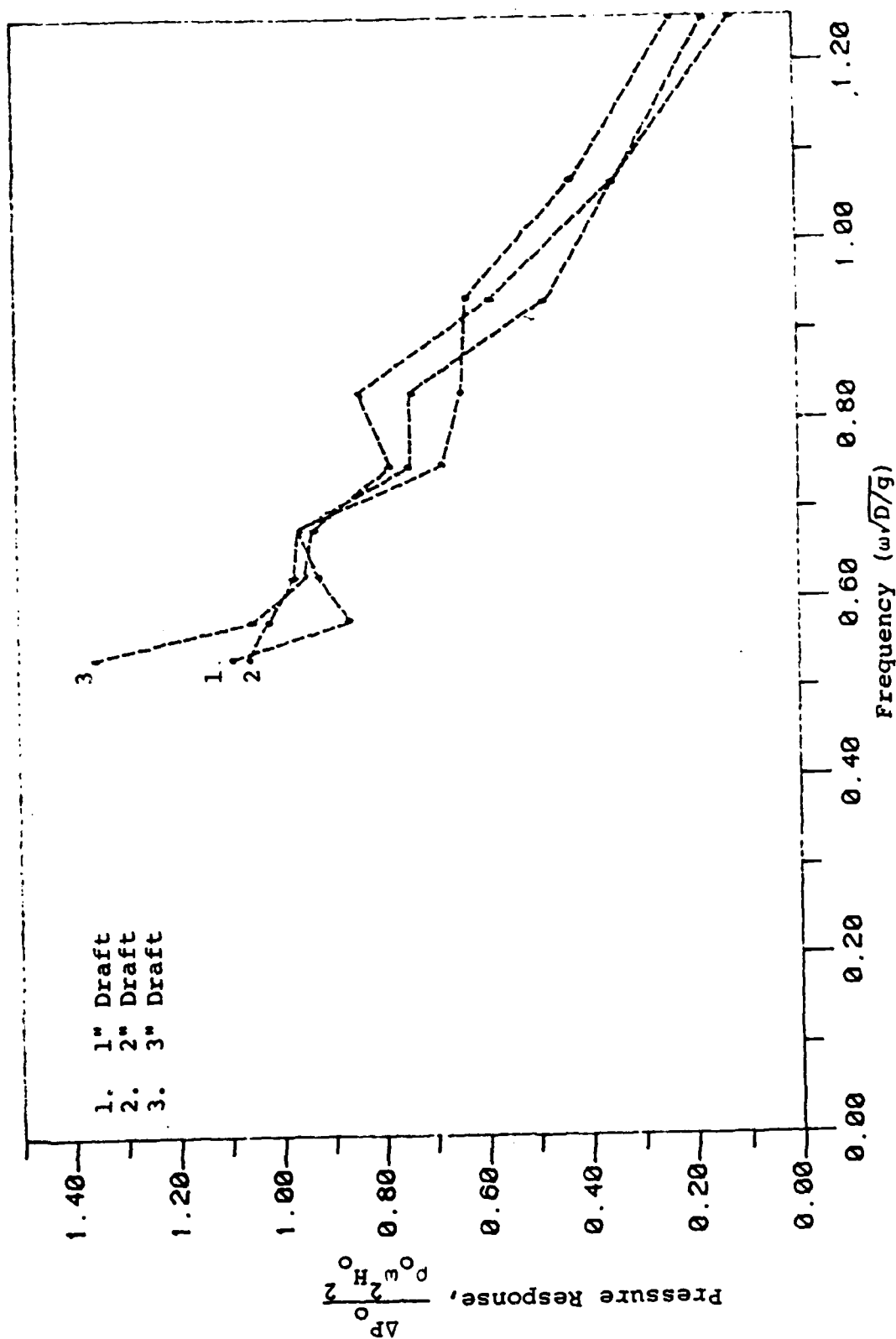


Figure 4.2 Pressure Response of 6" Cylinder, 1% orifice area

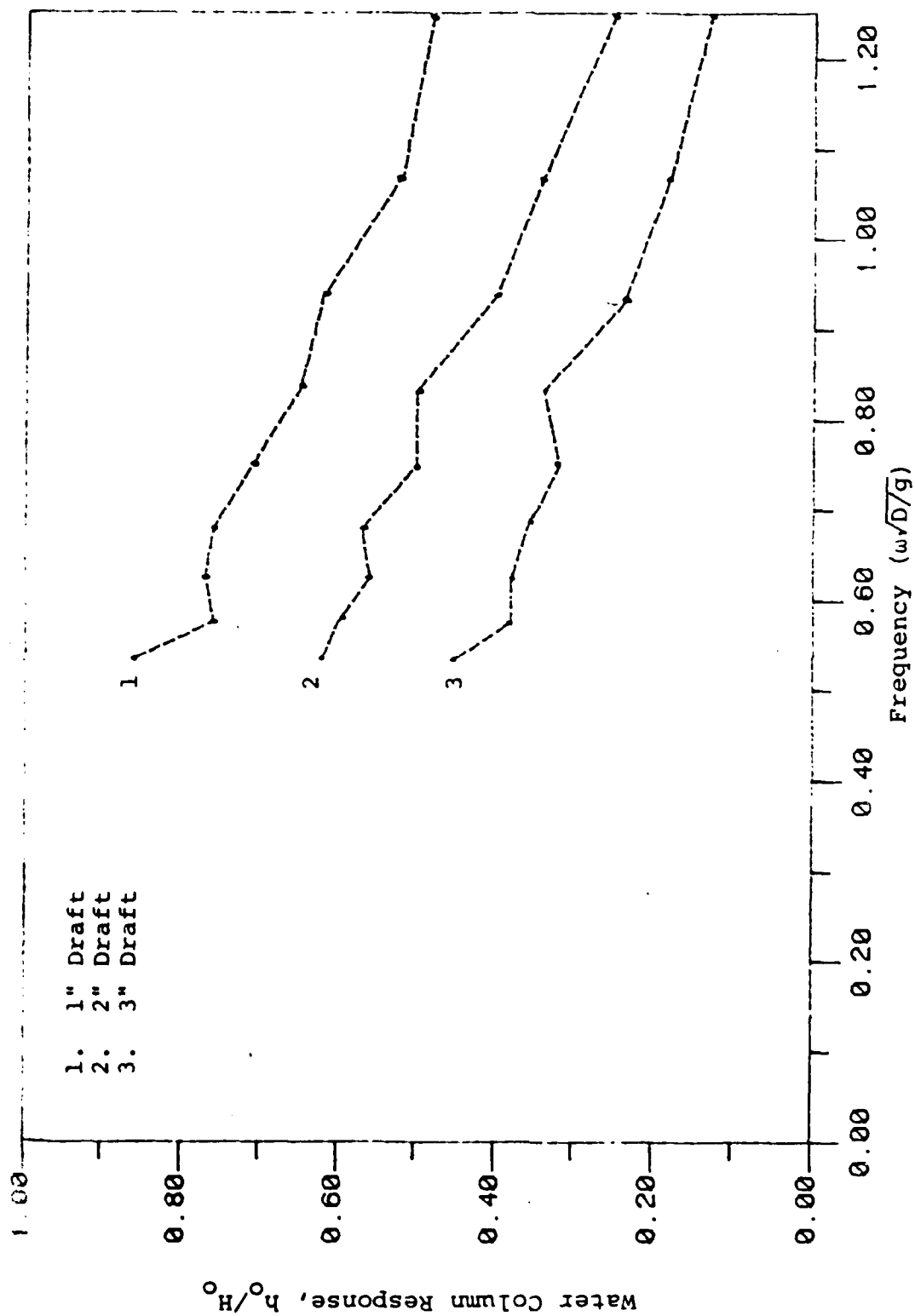


Figure 4.3 Water Column Response of 6" Cylinder, 1% orifice area

Figure 4.1 presents capture width/diameter,  $\ell/D$ , which is analagous to efficiency, for a range of depths or drafts. Figures 4.2 and 4.3 provide the measured air pressure and inside wave height data respectively, from the same tests (the results for the smallest draft were not included). The information from these tests will be utilized later to determine the size of the wave energy converter necessary to provide the power for the light tower.

The performance of a pneumatic device predicted from theoretical considerations by Evans [6] is also shown in Figure 4.1. The theoretical model assumes that the device has zero draft; this, of course, is impractical. However, there is good agreement between the predicted performance and the measured experimental performance at the smallest draft (i.e. 1/2 inch).

Tests were also conducted to see if the performance could be improved by controlling the air pressure inside the model to produce artificial resonant conditions. For this purpose a small plexiglas chamber was fabricated with two check valves and attached to the cylindrical model. The flow area of the check valves was designed to be much larger than the orifice area. One valve was to check the incoming air and the other to check the outgoing air. Electromagnets were inserted into the walls of the valve chamber to control the valve motion. A simple comparator and switching circuit was designed to

control the valves, such that the air pressure in the model would follow the outside incident wave height. The experiment was only moderately successful. The air pressure inside the model could be modified by the action of the controlling mechanism, but not enough to change the phase of the air pressure. It was determined that there was air leaking across the valves and that the comparator was not very sensitive. The leakage of air across the valves was a serious problem and could not easily be rectified.

The power of the model with the control system in operation was only slightly higher than the measured values without the controls. The wave forms of the air pressure signals, with and without, the control system are presented in Figure 4.4.

#### 4.3 CONCLUSIONS OF THE EXPERIMENTAL PROGRAM

The performance of the pneumatic wave energy converter determined from experiments confirmed the rather disappointing predictions of the theoretical studies. The measured values of maximum power absorbed by the device were only about 40 percent of the incident power. Furthermore, this peak power occurred at a rather high value of non-dimensional frequency. The influence of draft on the performance showed that the draft should be as small as is practical.

The experimental study of the phase control of air pressure inside the device was inconclusive. The air pressure

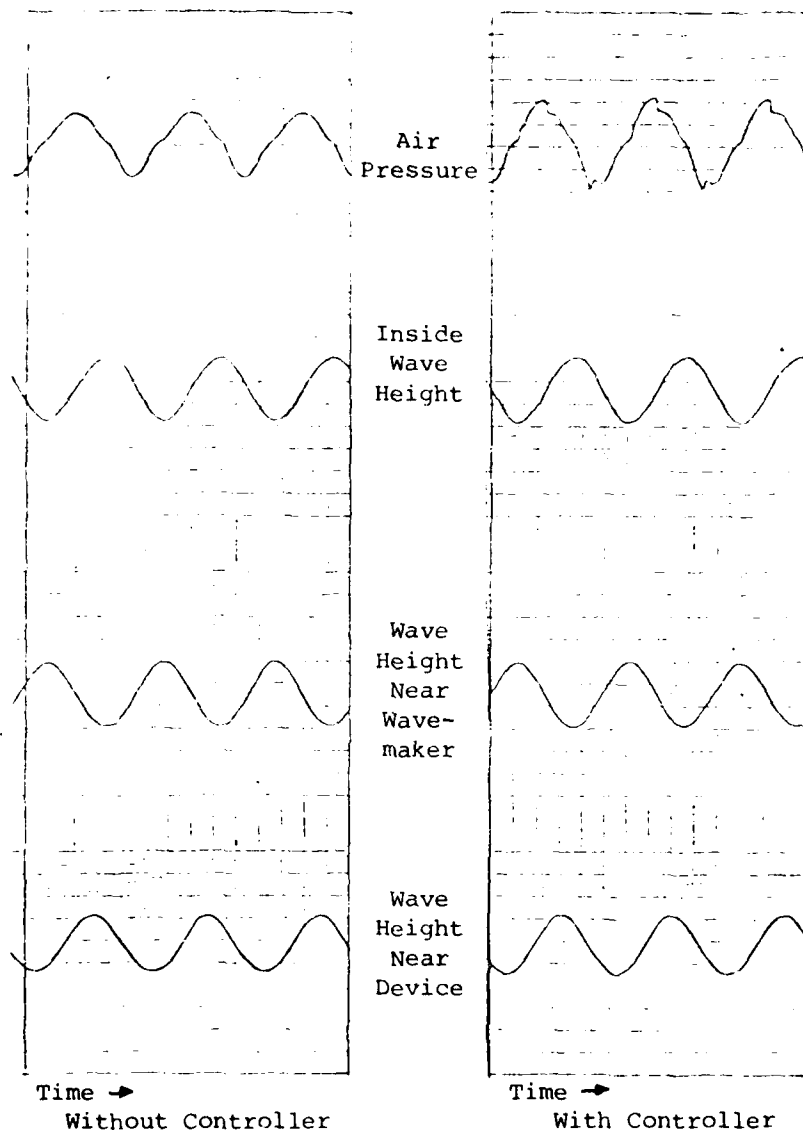


Figure 4.4 Comparison of the Air Pressure Inside the Wave Energy Device With and Without Controlled Valves, 6 Inch Model Period 0.8 Seconds.

could be modified by controlling the motion of the valves, but air leakage prevented the full potential of the procedure to be demonstrated.

## 5. CONVERSION TO ELECTRICAL POWER

In a pneumatic wave energy converter the power from the ocean waves is converted to an oscillating flow of compressed air. This flow of air in the full scale device would involve a complete reversal of the flow through the air turbine or air motor which is coupled to the electrical generator. In order to operate in such conditions, the turbine or motor should be capable of operating efficiently with outflowing and inflowing air from the air compression system driven by the waves. There appear to be two approaches:

- a. using a rectifying turbine
- b. using a control valve system in conjunction with a conventional turbine.

The rectifying turbine generates power whichever direction the air flows through it. In addition the turbine should rotate in the same direction, independent of the direction of the airflow. Several turbines have been proposed which have such characteristics. Probably the most well known is the Well's turbine, which has a very simple construction [9]. The turbine has a rotor which has an annulus in which there are several flat airfoils placed tangentially, such that the leading and trailing edges of each airfoil lie in the plane of the rotor (or wheel)



supporting the airfoils. The flat airfoils are more accurately described as zero-cambered symmetrical airfoils. It is obvious that because of symmetry the turbine operates with flow from either side of the rotor and rotates with the leading (rounded) edges of the airfoils indicating the direction of rotation. Experiments [9] on Well's turbines have shown that the starting torque is very low and that the efficiency of the units may only be about 60% at the best operating points. This type of turbine is not expected to be used for the light tower application.

A conventional air turbine can also be used in this application provided that a system of valves is used to direct the flow through the turbine. The Masuda Air Buoys utilize a system of check valves to rectify the flow through a small turbine coupled to a generator. Four check valves are required to provide complete rectification. To obtain the performance gains (discussed in the previous section) which are expected to be provided by the adjustment of the phase of the pressure change within the buoy, it would be necessary to control the motion of at least two of the valves. Two valves, one for each flow direction, would be controlled, while the remaining two valves could be regular check valves.

The air turbine, as stated above, would be of conventional design. It could be a scaled-up version of the Masuda "impulse" turbine or it could be a slightly more

efficient 50% reaction turbine of aircraft gas turbine design. With the 50% reaction design the turbine could be manufactured relatively inexpensively because the rotors and stators could be fabricated having the same blade shapes. It is expected that a conventional turbine with rectifying valves would be used for light tower applications.

A turbine-generator system coupled to a pneumatic wave energy converter obviously operates in a complex unsteady flow regime. Not only does the flow of air reverse with every wave but also ocean waves are irregular. The turbine-generator is therefore expected to have a lower average efficiency than a similar design operating with steady air flow at its design point. This loss in efficiency occurs because the turbine would operate inefficiently when the flow rate is low, but the loss can be minimized by controlling the field current in the generator.

The loss in performance in the turbine-generator has not been predicted for the preferred turbine-generator arrangement. However, a control system study was conducted for a Well's turbine coupled to a generator [10]. It was concluded from this investigation that with good design, about 70% of the pneumatic power could be converted into electrical power in regular waves, and that there would be an additional 5% conversion loss in random waves. These values were also expected to apply to the conventional air

turbine-generator arrangement proposed for the Buzzards Bay Light Tower.

If a modest peak turbine efficiency of 70% is assumed, then the overall conversion efficiency from pneumatic power to electrical power is 46%. This is a realistic value and is used, in the next chapter, as one component in the prediction of the average power output from the wave energy converter.

## 6. PREDICTED POWER OUTPUT

The test results from the 6 inch diameter model can be combined with the wave data at the Buzzards Bay site to provide performance predictions for full sized devices. The model data for the experiments conducted with 1 inch draft were utilized in this comparison because this arrangement had the best low frequency performance. The model device and a possible full scale arrangement are presented on Figure 6.1. Since potential improvements resulting from the control of the check valves have not yet been substantiated, it was not possible to include these expected improvements.

The model test results are presented on Figure 4.1 in the form of capture width/diameter,  $\lambda/D$ , plotted against non-dimensional frequency,  $\omega\sqrt{D/g}$ , where D is the diameter of the cylindrical wave energy converter. The concentration of wave power at various wave periods has been discussed earlier. The data for the Buzzards Bay site are summarized on Figure 2.2, which indicates that most of the power is available from waves having periods from 5 - 12 seconds. Utilizing the performance data for the six inch model and the power distribution data for the Buzzards Bay site it is possible to predict the expected average power for devices having a range of values of diameter.

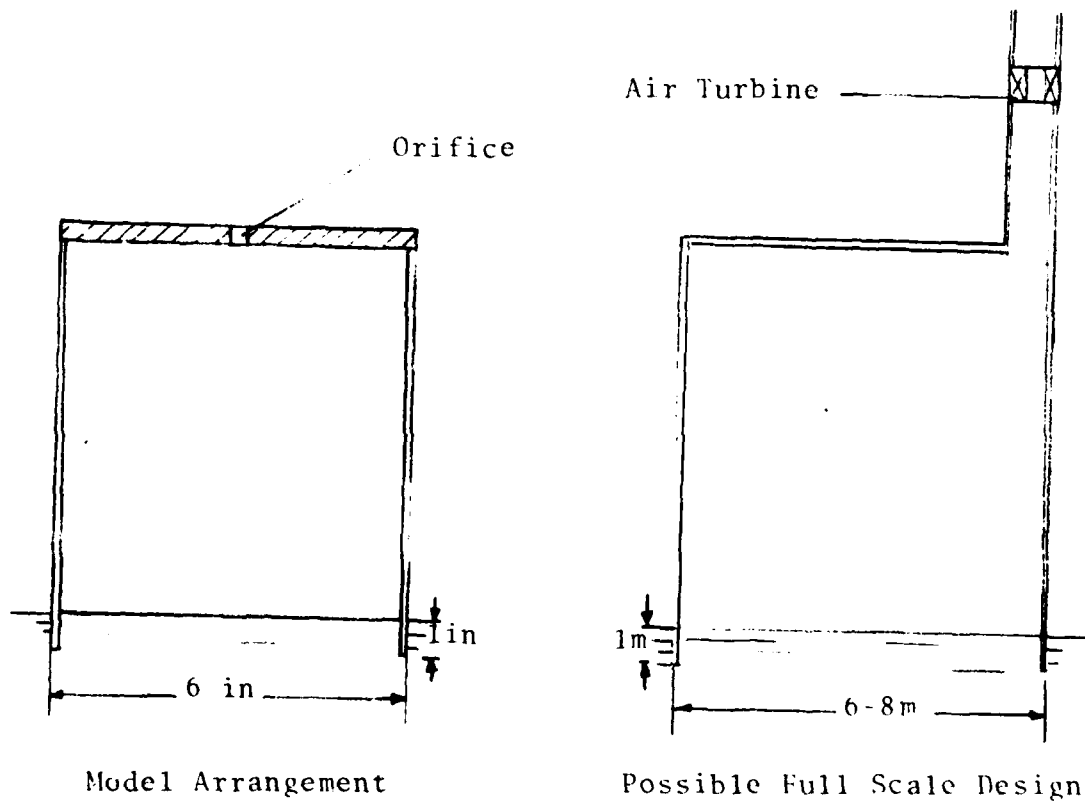


Figure 6.1 Arrangements of the Model and Possible Full Scale Wave Energy Converter

The process for any selected diameter is as follows:

The wave power distribution data for Buzzards Bay provides the expected wave power in kW/m in the various wave periods from 0 - 15 seconds in steps of one second period. At each of these periods, for the selected diameter, the non-dimensional frequency,  $\omega\sqrt{D/g}$ , can be calculated. At these values of  $\omega\sqrt{D/g}$  the capture width/diameter can be predicted from the model test results. The product of capture width/diameter and the expected wave power in each wave period gives the expected pneumatic power for the wave energy device at each wave period. The individual values of power are summed for the total range of wave periods from 0 - 15 seconds to predict the expected average power in kW per meter absorbed by the cylindrical device at the Buzzards Bay site. This power per meter is multiplied by the diameter in meters to provide an estimate of the pneumatic power of the device.

This calculation was carried out for devices having 4, 6, and 8 meters diameter.

The power delivered to the batteries is reduced from the pneumatic power because of friction and other losses in the turbine, generator, and conversion equipment. The overall conversion efficiency from pneumatic power to electrical power in the battery was discussed in the previous chapter and assumed to be 46%. This is a realistic value and when combined with pneumatic power predicted for the Buzzards Bay site it provides a reasonably conservative value for electrical power that can be made available at the batteries. The estimates for the pneumatic power and the electrical power at the batteries are presented on Figure 6.2. This

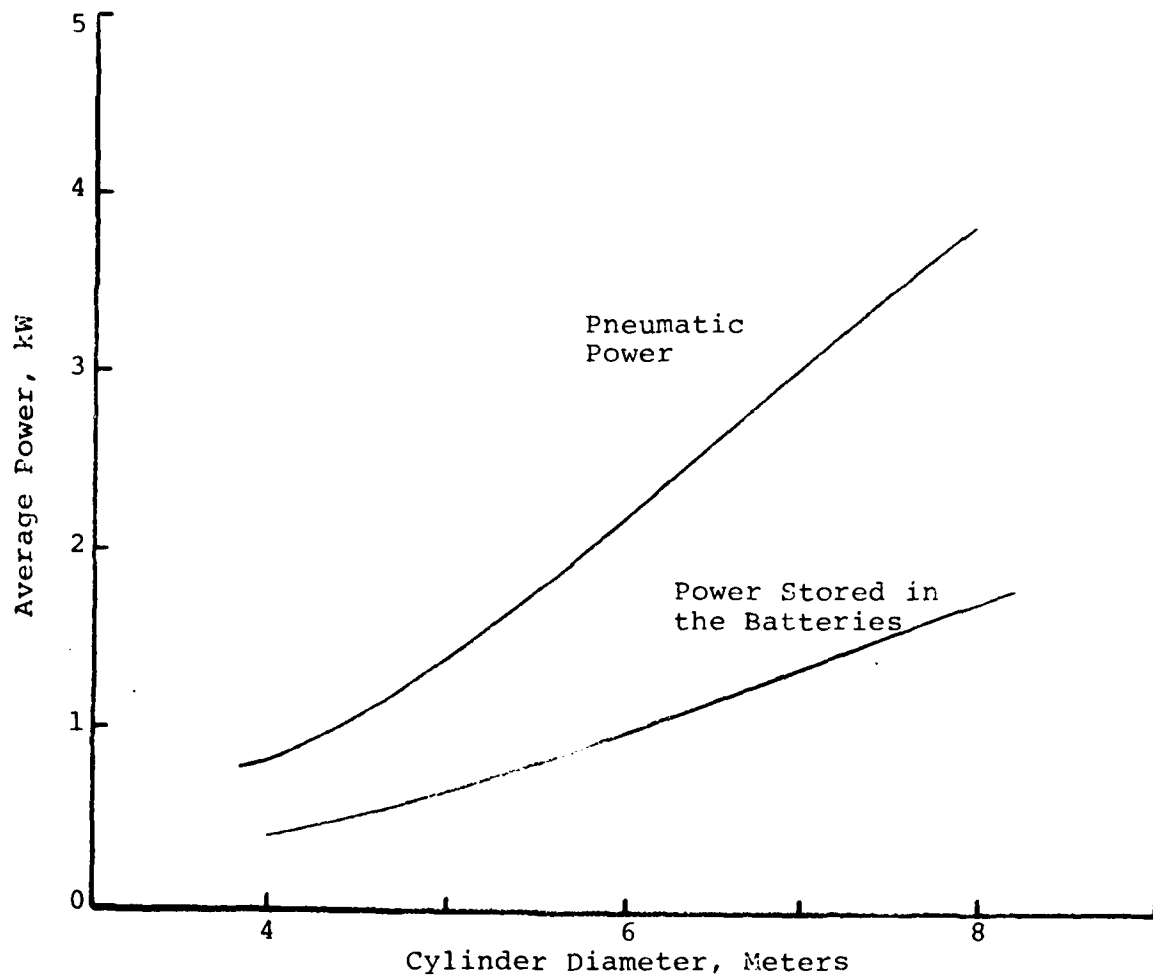


Figure 6.2 Estimated Performance of Cylindrical Pneumatic Buoys at the Buzzards Bay Tower

figure demonstrates that with a simple pneumatic system the diameter of the cylinder for the wave energy conversion device should be approximately 8 meters to provide the required average power of about 2 kW at the storage batteries for the Buzzards Bay Light Tower. The power outputs at the batteries for 6 meter and 4 meter devices are predicted to be only about 1 kW average and 0.4 kW average respectively, for the year.

The power output for the small devices is reduced compared with the large devices because their best operational performance, as observed in the experiments, occurs at relatively high frequencies (short periods) while the wave energy at the site is concentrated at low frequencies (long periods). As an example the 6 inch diameter model with a draft of 1 inch has the best test performance for non-dimensional frequencies,  $\omega\sqrt{D/g}$ , in the range 0.9 to 1.3. For a full scale device having a diameter of 4 meters these conditions for good performance correspond to wave periods of 3.1 to 4.5 seconds. Unfortunately, most of the wave energy at the Buzzards Bay site is concentrated in the periods 5 - 12 seconds.

It is anticipated that some gains in performance can be expected from controlling the check valves at the turbine. If these gains are realized then the size of the basic cylindrical device could be reduced.



7. WAVE LOADS ON THE WAVE ENERGY CONVERTER AND THE LIGHT TOWER STRUCTURE

It is expected that the wave energy conversion device will be rigidly attached to the light tower, therefore the latter will experience additional structural loads due to the waves. The need to maintain the integrity of the light tower under all weather conditions is expected to impose an upper bound on the physical size of the wave energy device at the site.

In this section of the report, the storm weather conditions are identified as the "one hundred year wave". An attempt is made to predict the wave height and period of this extreme wave from wave climate data collected at Buzzards Bay. These data are then used to determine the extreme loads on the wave energy device and the structure of the light tower.

7.1 EXTREME DESIGN WAVE

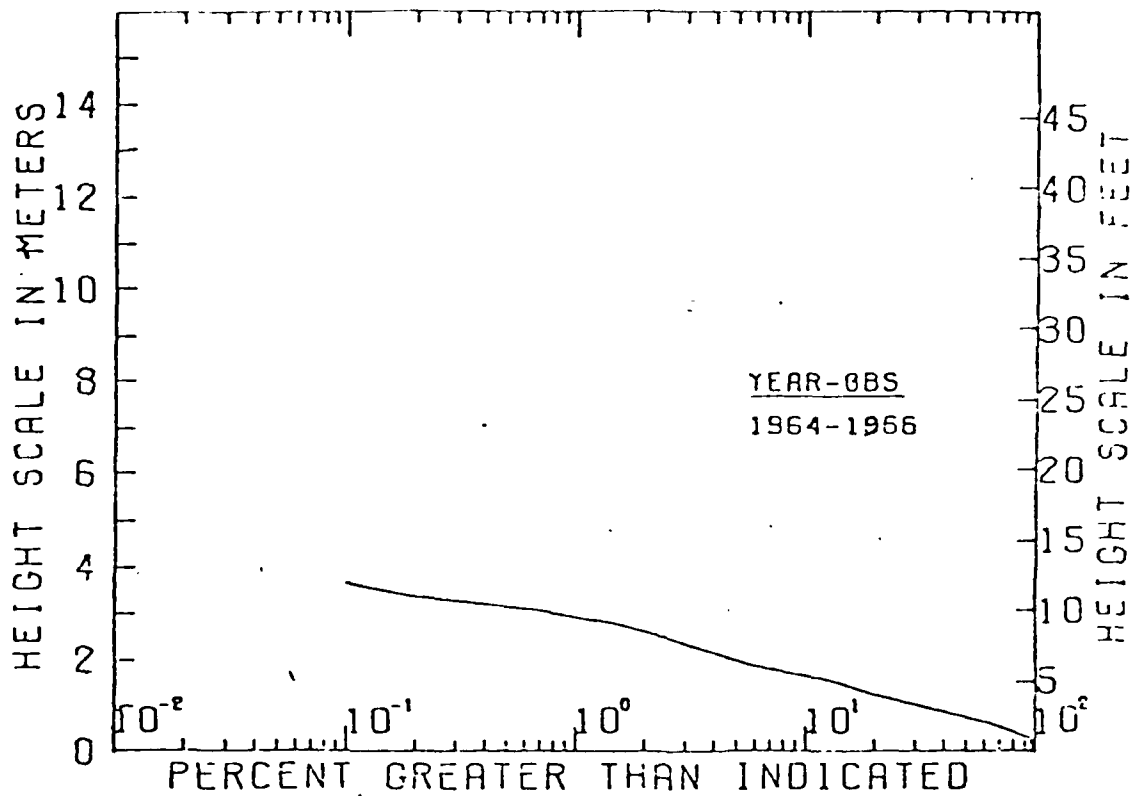
It is not really legitimate to extrapolate the extreme wave that might occur within a period of 100 years from wave height data collected during a relatively short period of 1 to 2 years. However, since the data described by Thompson [3] and shown in Figure 7.1, are all that appears to be available at the site, (it was collected during 1964 - 1966) it is necessary therefore to attempt to extrapolate the

Thompson results to provide an estimate of the one hundred year wave. A simple extrapolation assuming that the curve in Figure 7.1 is a straight line suggests that the maximum significant wave height during one hundred years is approximately 6 meters. Since the peak wave height is expected to be twice the significant wave height, this suggests that the maximum wave height during 100 years is 12 meters.

Another approach in extrapolating wave data is to fit a Weibull distribution to the data. The method requires three constants to be adjusted to give the best fit to the data. This process was carried out and the best curve was extrapolated to give the maximum wave height in 100 years. The 100 year peak wave was predicted to have a height of 13.2 meters. This value is larger than the simple extrapolation given earlier and was therefore used to determine the structural loads.

According to the rules of the classification society Det Norske Veritas the period in seconds of the 100 year wave is between  $\sqrt{6.5 H_{100}}$  and  $\sqrt{15 H_{100}}$ , where  $H_{100}$  is the maximum wave height in meters. The period is therefore between 9 and 14 seconds. For conservative design the lower value was used.

The selected conditions for determining the extreme structural loads are a wave height of 13.2 meters and a wave period of 9 seconds. The wavelength of the extreme wave is



Annual cumulative significant height distribution for Buzzards Bay, Massachusetts; determined from 7-minute pen and ink records taken six times daily.

Figure 7.1 Significant Wave Height at the Buzzards Bay Light Tower, (Thompson [3])

approximately 103 meters at the water depth in the region of the Buzzards Bay Tower. In addition to the wave action it was assumed that there would be a storm induced current of three knots.

## 7.2 STRUCTURAL LOADS

The conditions of the extreme wave may be utilized in conjunction with the semi-empirical Morrison equation [11] to predict the total forces (inertia and drag) acting on the Buzzards Bay Tower and on the wave energy device attached to the tower.

### 7.2.1 Predicted Loads on the Tower

The underwater structure of the tower shown in Figure 7.2, consists of 4 main steel tube members of 33 inches (0.84 meters) diameter, cross braced with 16 and 18 inch diameter circular members. The four main tube members are attached to piles which are driven about 200 feet into the mud onto bedrock.

For purposes of this study only the wave and current forces acting on the four main members were computed, that is the cross bracing members were not considered. The parameters that decide the dominant forces acting on the structure are the wavelength to diameter ratio;  $L/D$ , and the wave height to diameter ratio,  $H/D$ . For the four tube members of the tower  $L/D = 123$  and  $H/D = 15$ . The high value of  $L/D$  indicates that the structure of the waves will not be influenced by the

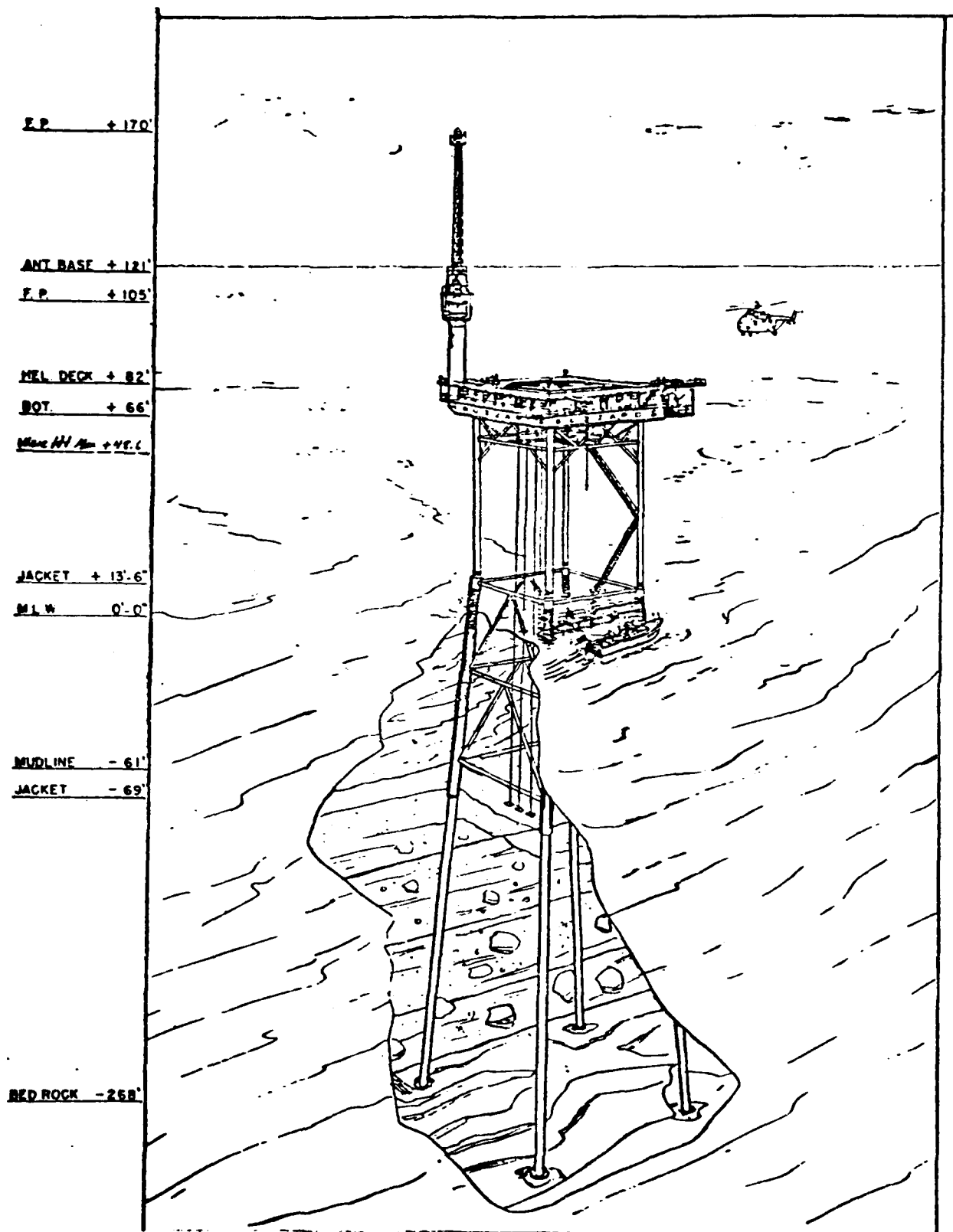


Figure 7.2 Arrangement of the Buzzards Bay Light Tower

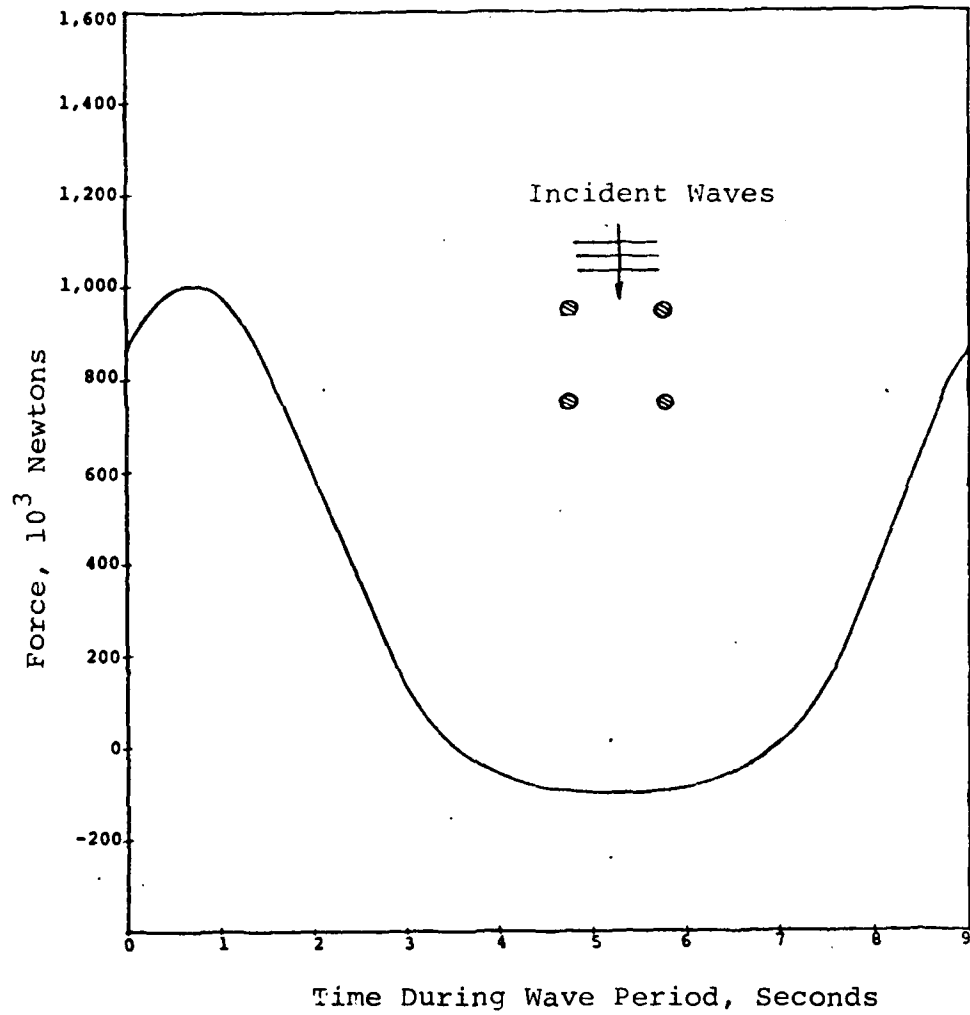


Figure 7.3 Load on the Structure of the Buzzards Bay Tower Due to a Storm Wave, Direct Waves

structural members, while the high value of  $H/D$  suggests that the drag forces dominate and that the inertia forces may be neglected.

The drag forces were calculated using a drag coefficient of 1.0. From the Reynolds number of the flow it was expected that the drag coefficient would be about 0.7. However, because of anticipated marine growth on the tubes, the higher value was selected.

The forces acting on the individual members of the tower can be calculated as a function of time, as the extreme wave passes the structure. The net load acting on the structure can then be determined by summing the forces acting on the individual components with due regard to the time at which the forces occur as the wave passes the different members of the structure. The forces acting on the structure were calculated for a wave striking the tower directly and in a diagonal direction. The total force acting on the four main members of the tower are presented on Figure 7.3 as a function of time, as the storm wave passes the structure.

#### 7.2.2 Predicted Loads on the Wave Energy Converter

The wave energy converter is a circular cylinder with the open end submerged one meter below the surface. This geometry is rather unusual in ocean engineering applications so that it is not possible to predict the loads with accuracy.

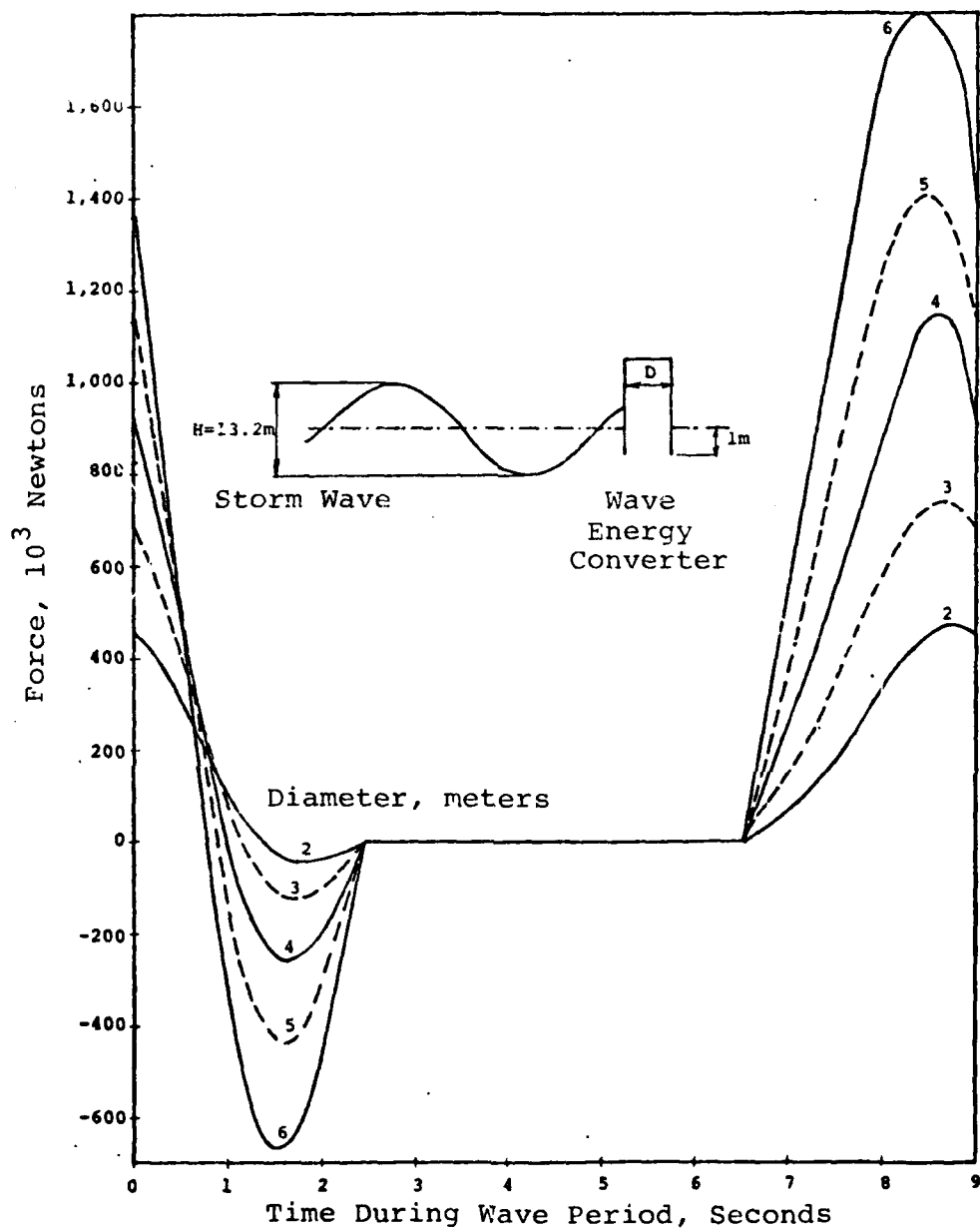


Figure 7.4 The Load on the Wave Energy Converter Due to a Storm Wave



A Morrison's approach was again utilized; which accounts for drag and inertia forces. The drag force is proportional to the square of the horizontal component of velocity while the inertia term is proportional to the horizontal component of acceleration. Hence these two forces are not in phase. Furthermore, the drag force is proportional to the product of the diameter and the length of the cylindrical wave energy converter while the inertia force is proportional to the product of the length and the diameter squared. The drag force was calculated assuming a drag coefficient,  $C_D$ , of 1.0 and the inertia force was calculated using an inertia coefficient,  $C_m$ , of 2.0.

The estimated total force on wave energy converters ranging in size from 2 meters diameter to 6 meters diameter are presented on Figure 7.4, plotted against time during the passage of an extreme wave.

#### 7.2.3 Predicted Combined Loads on the Light Tower and Wave Energy Converter

The wave energy converter was assumed to be rigidly attached to the light tower. In principle, the point of attachment could be selected so that the combined forces would be minimized. However, this was not considered to be a practical design because it could only be achieved with the wave energy converter cantilevered a considerable distance from the light tower. Furthermore, the direction of the extreme storm waves could not be guaranteed. Therefore, it

was decided to examine the storm wave forces resulting from the more practical arrangement, where the wave energy conversion cylinder was attached to one of the main vertical members.

The forces acting on the combination of the tower and a wave energy converter are presented on Figure 7.5 a and b for waves impinging normal to the light tower and in a diagonal direction. A 4 meter diameter wave energy converter was assumed to be rigidly attached to one of the main structural members of the Buzzards Bay Tower. It can be seen that the additional load due to a 4 meter diameter cylinder is very large (about  $800 \times 10^3 \text{ N}$  or 80 tons).

It appears that the loads imposed on the tower by a wave energy converter of even 4 meters diameter are prohibitively high. It is therefore concluded that the wave energy device should be designed to collapse before it overloads the structure.

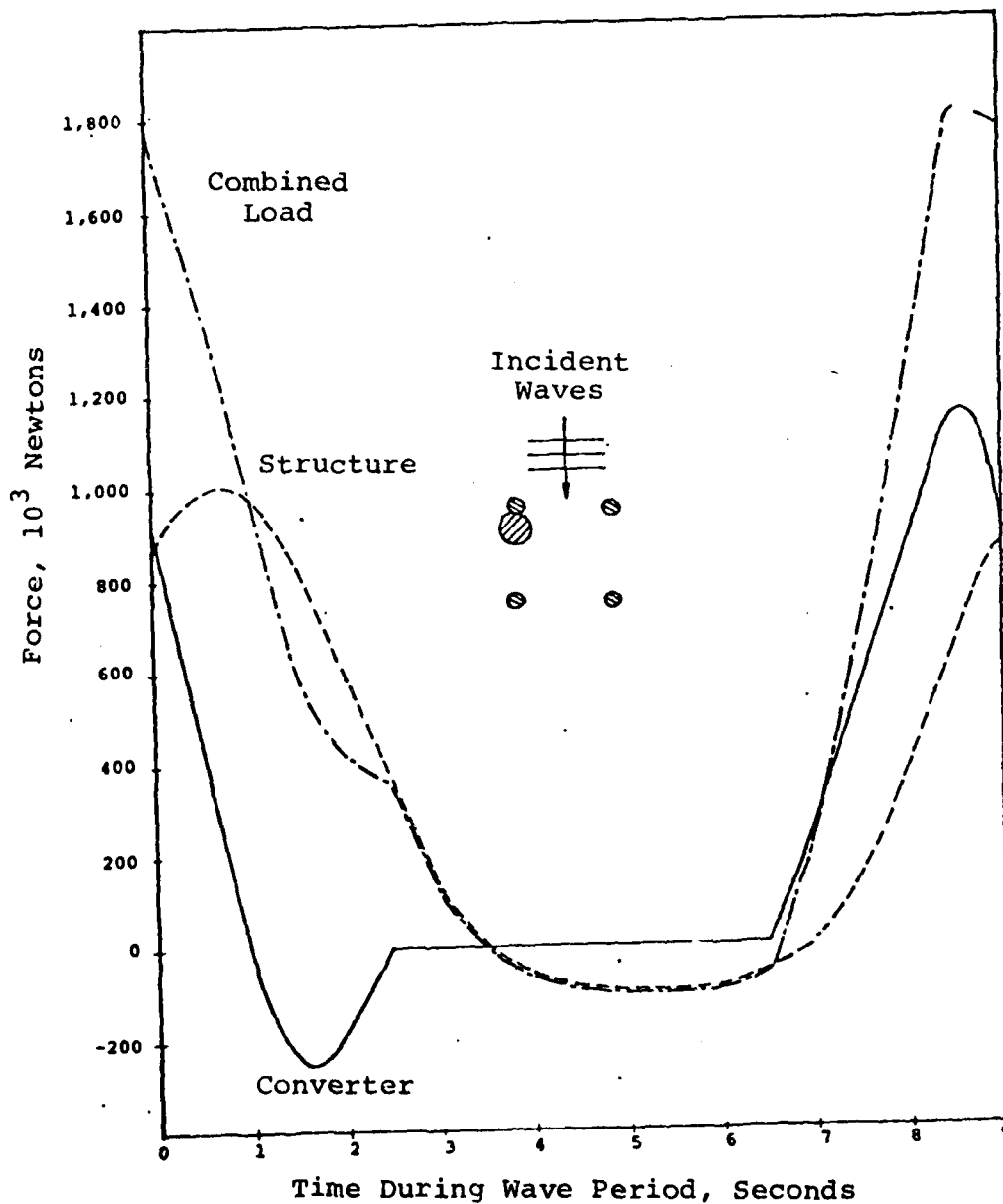


Figure 7.5a Loads on the Structure and the Wave Energy Converter Due to a Storm Wave, Direct Waves

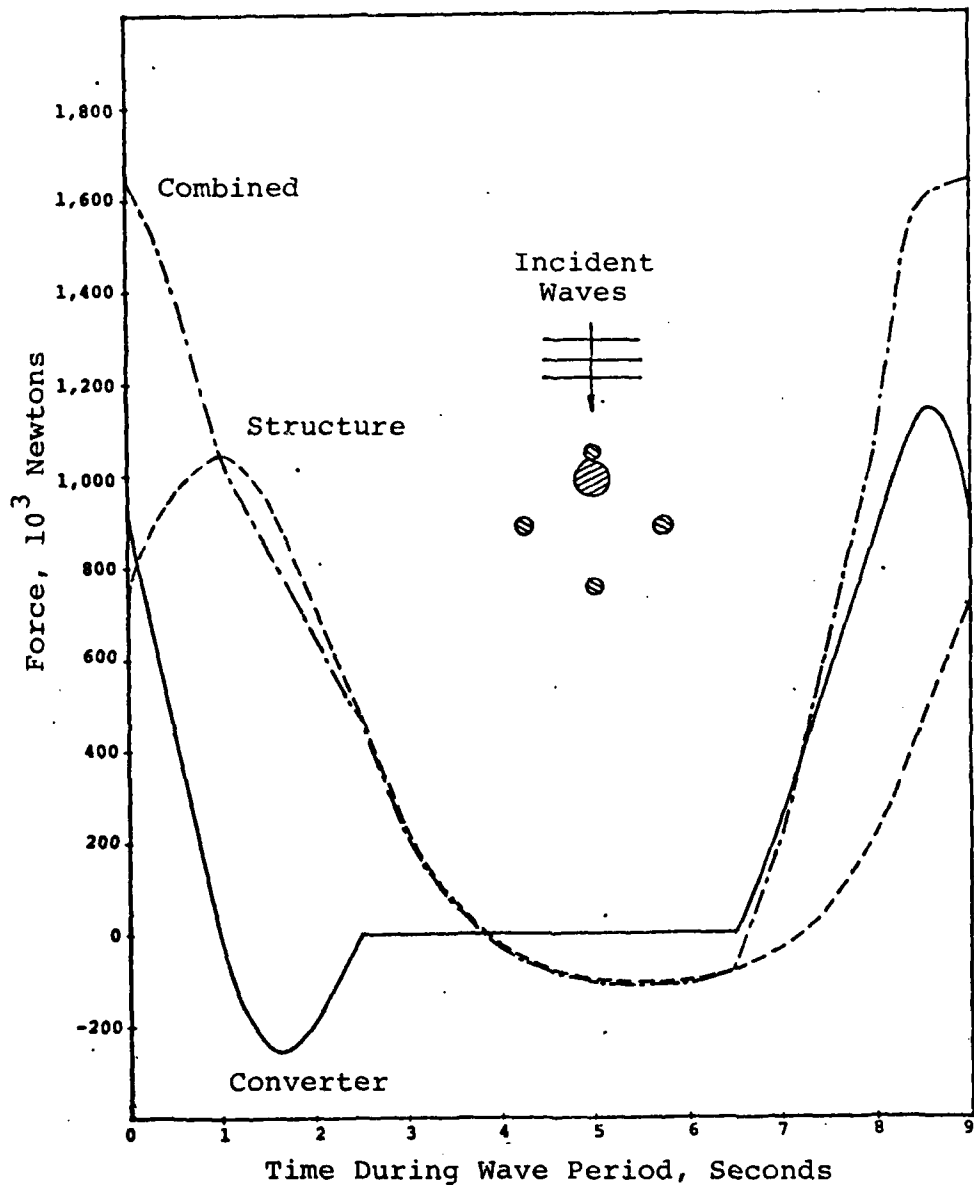


Figure 7.5b Loads on the Structure and the Wave Energy Converter Due to a Storm Wave, Diagonal Waves

## 8. CONCLUSIONS AND RECOMMENDATIONS

### 8.1 CONCLUSIONS

A study has been conducted to determine if it would be feasible and viable to utilize wave energy to provide the electrical power required, of approximately 2 kW average power, at the Buzzards Bay Light Tower. An examination of the available data on the wave climate at the tower indicated that the average wave power at Buzzards Bay is approximately 3.3 kW per meter of wave crest width. Much of the wave power is concentrated in wave periods between 5 and 12 seconds.

An examination of the various new devices that could be used at the Buzzards Bay Tower suggested that the more well known devices such as the Salter Duck and Hagen-Cockerell raft are unsuitable. It was concluded that a cylindrical buoy producing compressed air to drive an air turbine would probably be the most satisfactory device.

Hydrodynamic studies of ideal wave energy conversion devices have indicated that various types and geometries of devices have essentially similar performance characteristics. A published theoretical analysis [6] of an idealized model of a pneumatic wave energy converter has indicated that the performance would be disappointing. The device was predicted to absorb only about 40% of the incident wave power. However, it was concluded that the

power output could probably be increased using an active control system to control the air pressure inside the device to achieve artificial resonance.

An experimental program carried out in the Towing Tank at MIT provided the main focus of this study. Experiments were carried out on several geometries of pneumatic wave energy converters although most of the experiments were conducted on a six-inch diameter model. The model was placed in the Towing Tank at several drafts and it was determined that the best performance occurred at the shallow drafts. The performance of the pneumatic wave energy converter determined from the experiments confirmed the rather disappointing predictions of the theoretical studies. Some experiments were carried out using a controlled valve system but the results were inconclusive because of air leakage.

The conversion of pneumatic to electrical power would be accomplished by means of an air turbine. It was proposed that check valves would be used to rectify the flow in a conventional air turbine. The expected performance characteristics for such a turbine arrangement, combined with information on the wave environment at Buzzards Bay, and the experimental data from the small model pneumatic buoys provided the method for determining the power output as a function of size of the full-scale

pneumatic buoy system. It was concluded that an eight meter diameter device would be required to develop an average annual power of approximately 2 kW. With the controlled valve arrangement (which has not yet been validated) it may be possible to reduce the size of the wave energy converter.

The storm loads on the structure and on the wave energy converter have been predicted based on a 100 year wave, extrapolated from the wave climate data. The main result of this study is that a wave converter as small as 4 meter diameter would impose excessive loads on the structure. An 8 meter diameter device would probably be out of the question. It was, therefore, concluded that a wave energy converter of such a size would have to be designed to collapse before a critical load was imposed on the structure of the tower.

## 8.2 RECOMMENDATIONS

It is recommended that a small model of a pneumatic wave energy converter be built with a new design of controlled air valves in order to evaluate experimentally the concept of producing artificial resonant conditions.

REFERENCES

1. W.R. Powell, et al "Alternate Hybrid Power Sources for Remote Site Applications", U.S. Coast Guard, Report No. CG-D-06-81, February 1981.
2. B. Count (editor), Power From Sea Waves, Academic Press Inc. (London) Ltd., 1980.
3. E.F. Thompson, "Wave Climate at Selected Locations Along U.S. Coasts", U.S. Army Corps of Engineers, Coastal Engineering Research Center, Technical Report No. 77-1, 1977.
4. J.N. Newman, "Absorption of Wave Energy by Elongated Bodies", Applied Ocean Research, Vol. 1, No. 4, 1979.
5. D.V. Evans, "Power From Water Waves", Annual Review of Fluid Mechanics, 1981.
6. D.V. Evans, "Wave-Power Absorption by Systems of Oscillating Surface Pressure Distributions", J. Fluid Mech., Vol. 114, pp 481-499, January 1982.
7. K. Budal and J. Falnes, "Interacting Point Absorbers with Controlled Motion", Power from Sea Waves, B. Count (editor), Academic Press Inc. (London) Ltd., 1980.
8. J.O. Salsich, "An Experimental Evaluation of Pneumatic Wave Power Devices", S.M. Thesis, Department of Ocean Engineering, M.I.T., August 1981.
9. S. Raghunathan and W.J. McKay, "Characteristics of the Wells Turbine" Queen's University of Belfast, Department of Civil Engineering, Report No. WE/80/3R, 1980.
10. A. Bando, "Dynamics and Control of a Wave Power Conversion and Storage System", S.M. Thesis, Department of Mechanical Engineering, M.I.T., September 1981.
11. J.H. Milgram, "Waves and Wave Forces", Proceedings of BOSS '76, Vol. 1, Norwegian Institute of Technology, Trondheim, 1976. Also published as Report No. 76-19, MIT Sea Grant Program, November, 1976.